Journal of Cleaner Production 161 (2017) 188–199

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Global water transfers embodied in Mainland China's foreign trade: Production- and consumption-based perspectives

Mengyao Han [a, b, d], Michael Dunford [a, c], Guoqian Chen [d, *], Weidong Liu [a, b], Yilin Li [d, e], Siyuan Liu [f]

[a] Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, PR China
[b] Key Laboratory of Regional Sustainable Development Modeling, Chinese Academy of Sciences, Beijing 100101, PR China
[c] School of Global Studies, University of Sussex, Brighton BN19RH, United Kingdom
[d] Laboratory of Systems Ecology and Sustainability Science, College of Engineering, Peking University, Beijing 100871, PR China
[e] Department of Power Engineering, North China Electric Power University, Hebei 071003, PR China
[f] College of Mechanical Engineering, Yanshan University, Qinhuangdao 066004, China

A R T I C L E I N F O

Article history:
Received 24 January 2017
Received in revised form
3 April 2017
Accepted 6 May 2017
Available online 7 May 2017

Handling Editor: Yutao Wang

Keywords:
Embodied water
Water transfers
Globalization
China
Input-output analysis

A B S T R A C T

Water resources are embodied in global trade. Although China is the largest water withdrawal economy in the world, 50% of its direct water withdrawal is embodied in Chinese imports and exports. Due to an increasing division of activities between different production units, economies such as Mainland China mainly import intermediate products for further processing and then export final goods to other economies. Overall, Mainland China is a net embodied water supplier not only in final consumption-based trade relations but also in intermediate production-based ones. China's total per capita water use is much lower than the global average, but yet China exports embodied water through trade activities. Pakistan, Myanmar and India are China's largest embodied water suppliers, and Hong Kong, the United States and Japan are its largest net recipients. The main water exporting sectors in Mainland China are *Electrical and Machinery* (*Sector 9*) and *Textiles and Wearing Apparel* (*Sector 5*) respectively, and the main importing sector is *Agriculture* (*Sector 1*) with imports coming mainly from Myanmar, Pakistan, the United States and North Korea. This analysis of China's global embodied water transfers can inform policies to increase China's water use efficiency and can be generated to build embodied water budgets for a systematic allocation of water resources on the globe especially from the production- and consumption-based perspectives.

1. Introduction

Global supply chains establish connections among countries and regions. To satisfy water demands, water grabbing through commodity trade has been deemed an effective strategy especially for water-deficient regions (Rulli et al., 2013). As a result, water embodied in merchandise trade plays a substantial role in balancing local, national and global water budgets (Davis and Caldeira, 2010; Yu et al., 2013).

To measure the water embedded in global supply chains, Allan (1993) advanced the concept of virtual water to suggest ways of dealing with water shortages in the Middle East. As agricultural water withdrawals account for a vast majority of global freshwater use (Hoekstra and Chapagain, 2007; Konar et al., 2011; Oki and Kanae, 2004), the first virtual water studies mainly focused on the water embedded in crops. By measuring evapotranspiration, different crops' water footprints, defined as the water utilized by a process or a product's entire value chain, were extensively analyzed and assessed (Chapagain and Hoekstra, 2007; Chapagain et al., 2006; Gerbens-Leenes and Hoekstra, 2012; Tuninetti et al., 2015). On the basis of these studies, the Water Footprint Network published a manual that contained a complete and consistent method to guide water footprint assessment (Hoekstra et al., 2009). This concept was further extended to livestock (Chapagain and Hoekstra, 2003; Hanasaki et al., 2010) and industrial products (Chapagain and Hoekstra, 2008). Furthermore, the integration of water use with international food trade statistics enabled researchers to examine the virtual water embedded in global (Dalin

* Corresponding author.
E-mail address: gqchen@pku.edu.cn (G. Chen).

http://dx.doi.org/10.1016/j.jclepro.2017.05.024
0959-6526/

et al., 2012; Hoekstra and Chapagain, 2007; Hoekstra and Hung, 2005; Konar et al., 2011; Liu et al., 2009) and regional trade (Dalin et al., 2014; Dang et al., 2015; Duarte et al., 2014; Liu et al., 2007).

Besides the above mentioned studies, two distinctive input-output analysis (IOA) methods are employed in water resources accounting. One is the environmentally-extended IOA (Leontief, 1970, 1986) as an extension of the standard economic IOA (Leontief, 1936). Leontief's (1986) input-output analysis (IOA) played a significant role in describing the relationship between inputs and outputs. It was further extended to frequently analyze resource and environmental issues (Lenzen et al., 2013a; Peters and Hertwich, 2008) by expressing the total output as a function of final consumption. In particular in order to examine the water embedded in trade, input-output analyses were conducted at global (Daniels et al., 2011; Lenzen et al., 2013a; Llop, 2013), national (Dalin et al., 2014; Duarte et al., 2002; Ewing et al., 2012; Guan and Hubacek, 2007; Zhao et al., 2009), and urban scales (Dietzenbacher and Velázquez, 2007; Wang et al., 2009, 2013; Velázquez, 2006; Zhao et al., 2016). Besides, the input-output data were also analyzed combined with ecological network analysis to build the socio-economic network (Chen and Chen, 2012a; Fang and Chen, 2015, 2017; Fang et al., 2014).

Systems IOA, another accounting method originated from Odum's ecological and general systems theory (Odum, 1983). Odum's system ecology and general systems theory examined the inherent energetic hierarchical structure in general ecological systems, in terms of the concept of embodied energy to measure the total energy both directly exploited from the environment and indirectly as feedback from the ecological system. For economy as a special subset of the ecological system, Herenden (1974), Costanza (1980) and Costanza and Herenden (1984) calculated the embodied energy required to produce goods and services by use of the economic input-output table. This method was developed to measure ecological elements as environmental resources embodied in economic activities (Chen et al., 2012; Han et al., 2015b; Li et al., 2015, 2016; Shao, 2014; Xia et al., 2015a, b). Various scales assessments including global (Chen and Chen, 2012b; Chen et al., 2012), national (Chen and Chen, 2010; Guo and Shen, 2014), regional (Liu et al., 2016), and urban scales (Chen and Li, 2015; Han et al., 2015a; Li and Chen, 2014; Shao et al., 2016) were conducted. External exploitation exogenous to the economy was regarded as the embodiment in the total product delivery to reflect the total output including both final entries and intermediate products (Chen and Chen, 2010).

Among these studies, Lenzen et al. (2013a) incorporated water scarcity, defined as the varying degrees of water shortage in different regions, into an assessment of global water flows by using a water scarcity index as a weight for converting total water use into scarce water use. Chen et al (Chen and Chen, 2012b; Chen et al., 2012). assessed the water use trade connections by input-output analysis and measured water use dependency of different countries. Yu et al. (2014) assessed the unequal exchanges between China and the rest of the world, especially focusing on SO_2 and carbon emissions, water resources and land use. IOA analysis was also used to assess China's multi-regional virtual water use (Liu et al., 2007; Zhao et al., 2009) and suggested that virtual water trade involves transfers from regions with higher water pressure to areas with lower water pressure (Zhao et al., 2015).

The above-mentioned efforts contributed significantly to the use of input-output analysis for water resources accounting, in particular in relation to global water scarcity and water distribution (Chen et al., 2012; Daniels et al., 2011; Lenzen et al., 2013a; Llop, 2013). Existing water resources studies have provided analyses of water use in industrial sectors and economic regions (Colosimo and Kim, 2016; Han et al., 2014; Vassallo et al., 2016). However, analyses of China's embodied water transfers via supply chains from production- and consumption perspectives and particularly of embodied water trade pressure and patterns are still lacking.

To help fill this gap, this article uses multi-regional IOA to examine the water transfers embodied in Mainland China's trade flows distinguishing trade in intermediate products and in goods entering final consumption with the rest of the world. The remainder of the paper is structured as follows: Section 2 articulates the method employed in this study, Section 3 analyzes the results, Section 4 discusses the policy implications, and Section 5 draws some conclusions.

2. Method and materials

Input-output tables, in particular multi-region input-output tables, were often employed to explore economic interdependence and to assess the impacts embedded in economic activities including energy use (Chen and Chen, 2013; Chen and Wu, 2017; Xia and Chen, 2012), greenhouse gas emissions (Peters and Hertwich, 2008; Shao et al., 2016), water use (Lenzen et al., 2013a; Shao and Chen, 2013), and land displacement (Chen and Han, 2015a, b; Guo et al., 2014; Weinzettel et al., 2013). In this study the multi-regional input-output analysis is used to examine the interaction of ecological resource demands and national/international economic transactions to reveal the resource flows associated with economic flows.

Table 1
Extended multi-regional resources use input-output table for the world economy.

<table>
<tr><td colspan="2" rowspan="3">Output / Input</td><td colspan="11">Intermediate production</td><td colspan="5">Final consumption</td></tr>
<tr><td colspan="3">Region 1</td><td rowspan="2">…</td><td colspan="3">Mainland China</td><td rowspan="2">…</td><td colspan="3">Region m</td><td rowspan="2">Region 1</td><td rowspan="2">…</td><td rowspan="2">Mainland China</td><td rowspan="2">…</td><td rowspan="2">Region m</td></tr>
<tr><td>Sector 1</td><td>…</td><td>Sector n</td><td>Sector 1</td><td>…</td><td>Sector n</td><td>Sector 1</td><td>…</td><td>Sector n</td></tr>
<tr><td rowspan="3">Region 1</td><td>Sector 1</td><td colspan="11" rowspan="11">z_{ij}^{rs}</td><td colspan="5" rowspan="11">f_i^{rs}</td></tr>
<tr><td>…</td></tr>
<tr><td>Sector n</td></tr>
<tr><td colspan="2">…</td></tr>
<tr><td rowspan="3">Mainland China</td><td>Sector 1</td></tr>
<tr><td>…</td></tr>
<tr><td>Sector n</td></tr>
<tr><td colspan="2">…</td></tr>
<tr><td rowspan="3">Region m</td><td>Sector 1</td></tr>
<tr><td>…</td></tr>
<tr><td>Sector n</td></tr>
<tr><td colspan="2">Resources use</td><td colspan="11">w_i^r</td></tr>
</table>